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# Time-dependent uplift capacity of driven piles in low to medium density chalk

F. CIAVAGLIA\*, J. CAREY\* and A. DIAMBRA†

A series of load tests have been performed on instrumented 762 mm dia. tubular steel piles driven into low to medium density grade A/B chalk at St Nicholas at Wade, Kent, UK. This paper presents the results from the static axial uplift tests, which were performed on two piles 7, 50 and 120 days after installation in order to investigate the time-dependent variations in shaft resistance. The results show that the static ultimate shaft resistance of this type of chalk can increase by up to a factor of seven over this time period, as a consequence of ‘set-up’ effects. The test results also show that the ‘set-up’ effect is reduced if the pile is subject to lateral loads up to 50% of the ultimate lateral capacity before uplift loading, while the application of lateral loading up to 10% of ultimate lateral capacity had negligible influence on axial capacity. The measured load distribution from strain gauges suggests a mobilisation of larger unit shaft resistance in the lower half of the pile. This paper also describes the geotechnical site conditions, the pile instrumentation and the effects of pile driving on the chalk.

**KEYWORDS:** chalk; offshore engineering; piles & piling

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## NOTATION

$D$	pile outside diameter
EL	pile embedded length
$f_s$	pile unit shaft resistance
$L$	pile total length
WL	pile wall thickness

## INTRODUCTION

Earlier to this research, very few pile tests had been carried out on driven piles in chalk. These limitations are reflected in Ciria C574 (Lord *et al.*, 2002), which represents the current state-of-the-art of engineering in chalk.

Lord *et al.* (2002) explained that when piles are driven into low density chalk, the blocks are easily fractured and crushed to a paste due to the low intact strength of chalk. An annulus of remoulded chalk is formed around the pile, which appears to cause a reduction in lateral stress. As a result of this, piles driven into this material generally experience low resistance to driving (with a unit shaft resistance during driving of 0–20 kPa) and a typical short-term static unit shaft resistance of ~20 kPa (Lord *et al.*, 2002).

The Ciria C574 guidance for engineering in chalk (Lord *et al.*, 2002) recommends using an ultimate shaft resistance of 120 kPa for the pile design in high density grade A chalk, and 20 kPa for all other densities or grades. These recommendations were based on the results of only two pile tests in medium to high density chalk (Lord & Davies, 1979; Hobbs & Atkinson, 1993) and two tests in low density chalk (Hobbs & Robins, 1976; Burland & French, 1990). However, the Ciria C574 guidance (Lord *et al.*, 2002) also points out that ‘pore water pressures in the remoulded chalk dissipate with time, so that a pile can generate a higher shaft resistance if there is a longer delay between driving and testing’. This is referred to as ‘set-up’. Vijayvergiya *et al.* (1977) found that

set-up can increase the static axial capacity of piles in low to medium density chalk by a factor of 1.1 after 1 h and by a factor of 1.8 after 60 days.

On the basis of a review of the current state-of-the-art, the ultimate shaft resistance and its variation with time was seen as one of the most pressing issues related to driven piles in chalk. As such, static uplift tests at different times after installation were performed on open-ended steel tube piles, which were installed as part of a broader research project that also involved static and cyclic lateral tests (Wind Support, 2012).

## SITE DESCRIPTION

The test site is a disused chalk pit located in St Nicholas at Wade, Kent, UK. The chalk is Ciria grade A/B (Lord *et al.*, 2002) low to medium density and all the superficial weathered chalk has been removed by previous quarrying activity. The site was investigated by nine cone penetration tests (CPTs) and five boreholes up to 20 m depth below ground level (SEtech, 2007; FGC, 2012a, 2012b) and by the performance of two cyclic CPTs (Diambra *et al.*, 2014). Two typical CPT profiles in the vicinity of the two tested piles are reported in Fig. 1. The chalk was found to be within 0.5% of a fully saturated state, even though the groundwater level was about 10–11 m below ground level. A summary of the key chalk properties is presented in Table 1.

## PILE CHARACTERISTICS AND INSTRUMENTATION

Two piles were subjected to static axial uplift tests and they are named pile 1 and pile 2. Both piles had an outside diameter ( $D$ ) of 762 mm, wall thickness (WL) of 44.5 mm, total length ( $L$ ) of 5 m and an embedded length (EL) of 4 m. The steel grade was API 5L X65.

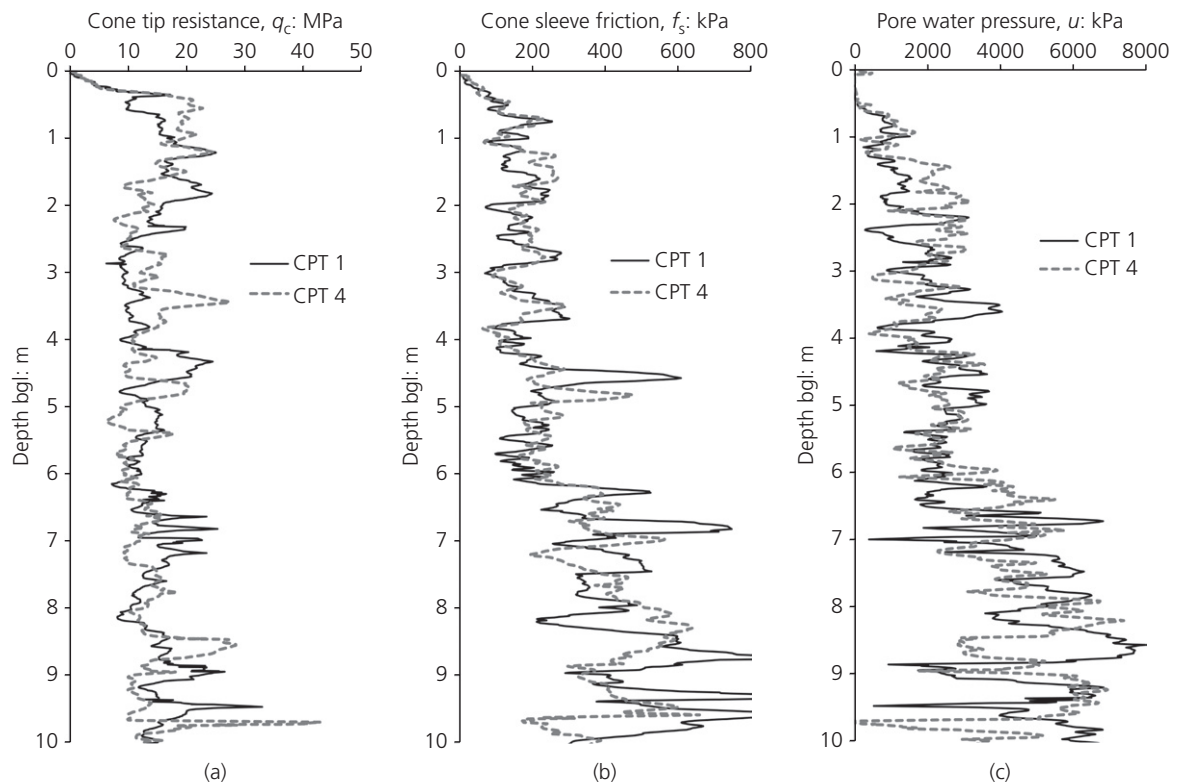
Vertical movements of the pile head were recorded by four linear variable displacement transducers. Twenty vibrating wire strain gauges were welded in pairs at diametrically opposite positions (Fig. 2(a)) at selected depths along the piles (Fig. 2(b)). To avoid damage during driving, angular steel channels were welded over the gauges and each channel was closed at the pile toe using a 90° tapered steel plate with a nominal height of ~100 mm (Fig. 2(c)).

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**Fig. 1.** Typical CPT results including: (a) cone tip resistance ( $q_c$ ), (b) sleeve friction ( $f_s$ ) and (c) pore pressure ( $u$ )

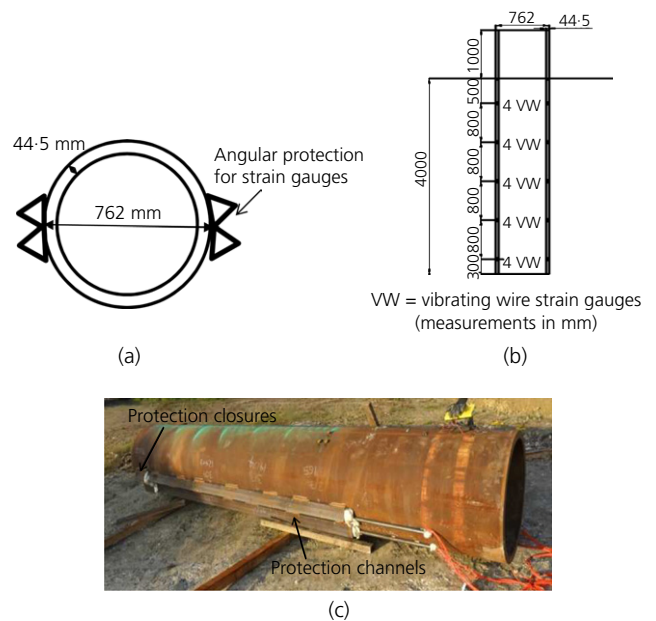
**Table 1.** Key chalk properties at test Kent site

Chalk formation	Within the Margate chalk member and upper part of the Seaford chalk formation of the White chalk subgroup
Ciria grade	Grade A/B
Bulk density: $\text{mg/m}^3$	Average 1.94 (range 1.88–2.09)
Dry density: $\text{mg/m}^3$	1.5 (1.38–1.73)
Saturation moisture content: %	29.5 (21–33)
Porosity: %	44 (36–47)
Unconfined compressive strength: MPa	2.4 (2.1–3.3)

## PILE INSTALLATION

The piles were driven using a 7 t hammer (7T Junttan PM20) as shown in Fig. 3(a). The measured blow counts against pile penetration depth (Fig. 3(b)) show an easy driving to target depth for both the piles. The drop height of the hammer ram was varied between 100 and 400 mm, to suit the driving resistance.

During pile driving installation, the chalk got displaced by moving up inside the pile, raising the internal chalk level by  $\sim 1.5$  m (Fig. 4(a)). It was estimated that the volume of this displaced chalk was approximately equal to the volume of steel driven below ground level. This suggests that the preferential 'flow path' for the displaced chalk was up inside the piles. It was also observed that all the chalk inside the pile became completely disturbed by the action of driving. The preferential flow path was likely due to the very low resistance of the completely disturbed chalk inside the pile, including the very low internal shaft resistance. For a large diameter pile, where the chalk in the very centre of the pile is likely to remain intact, a preferential flow path up the inside of the pile is not envisaged. Instead, it is expected that the chalk will be displaced outside the pile just as easily as inside.



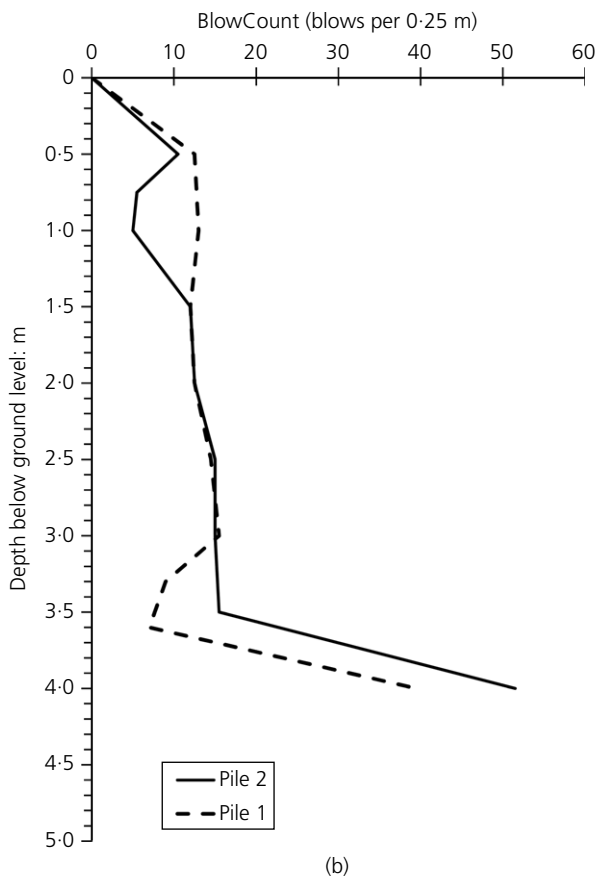
**Fig. 2.** Pile instrumentation: (a) pile cross-section, (b) strain gauge positions and (c) pile showing angular strain gauge protection

As the chalk rose inside the pile and came into contact with the hammer, significant damping occurred as the hammer tried to compress the chalk. This meant that driving had to be stopped several times to remove the excess chalk before the pile driving could continue. This damping effect accounts for the increase in blow count after 3.5 m penetration, as shown in Fig. 3(b).

There was no obvious gap between the piles and the surrounding soil at the completion of the driving process;



(a)



(b)

**Fig. 3.** (a) Driving operations, (b) driving blow count against pile installation depth

however, some slight heave (Fig. 4(c)) was observed around the outside of the piles during driving, which remained after driving was completed. External to the piles, the chalk remained relatively undisturbed and intact, apart from a remoulded annulus that was ~20–40 mm thick (Fig. 4(b)) and a zone of a fractured chalk extending 500 mm beyond the pile wall. Muir Wood *et al.* (2015) also found that driving steel plates of different thicknesses into low to medium

density chalk (at the same Kent test site) creates a zone of remoulded chalk adjacent to the plates, with a typical width of around 40% of the plate thickness.

A restrike test was carried out on pile 1, 2 h after installation and on pile 2, 12 h after installation. The restrike blows were monitored using a pile driving analyser and the data were analysed using case pile wave analysis program (CAPWAP) software. The results indicated an average shaft resistance of 11 kPa and unit end bearing of 6.5 MPa for pile 1 (2 h after installation) and an average shaft resistance of 23 kPa and unit end bearing of 9.2 MPa for pile 2 (12 h after installation).

#### PILE LAYOUT AND TESTING STRATEGY

The pile layout is provided in Fig. 5, where the locations of the boreholes and CPTs are also mapped. Piles 3–5 (marked in grey in Fig. 5) were also driven as part of the same test campaign but tested under lateral loading only and these results have been discussed in Ciavaglia *et al.* (2017) and Wind Support (2012).

The uplift tests on pile 1 and pile 2 were performed in three phases at different times (2–6 days, about 7 weeks and about 4 months) after pile installation as reported in Table 2. The main purpose of the tests performed on pile 1 was to investigate possible time-dependent variations in pile behaviour following installation, which might be caused by the dissipation of positive excess pore pressures or recementation of the remoulded chalk as suggested by Lord *et al.* (2002). The tests on pile 2 were used to determine if lateral loading can affect the build-up of shaft resistance over time. Pile 2 was subjected to monotonic lateral loads up to ~10% its ultimate lateral pile capacity (determined to be about 2500 kN on lateral loading to failure, Wind Support, 2012) before tests 2\_A7 and 2\_A52 (carried out 7 and 52 days after installation, respectively), and up to 50% ultimate lateral pile resistance before test 2\_A122 (carried out 122 days after installation).

#### UPLIFT TESTS RESULTS

##### Load–displacement curves

The load–displacement curves obtained during the pile 1 and 2 test series are shown in Fig. 6. Pile 1 shows a very large increase in uplift capacity with time after installation. The capacity at 7 weeks is about twice the capacity after 2 days after driving, while the capacity after 4 months is about six times higher (Fig. 6(a)). The load–displacement curves display almost bilinear behaviour up to the failure point with the yield point being at about 5 mm for the first two tests (1\_A2 and 1\_A50) and at a higher displacement for the final test (1\_A119).

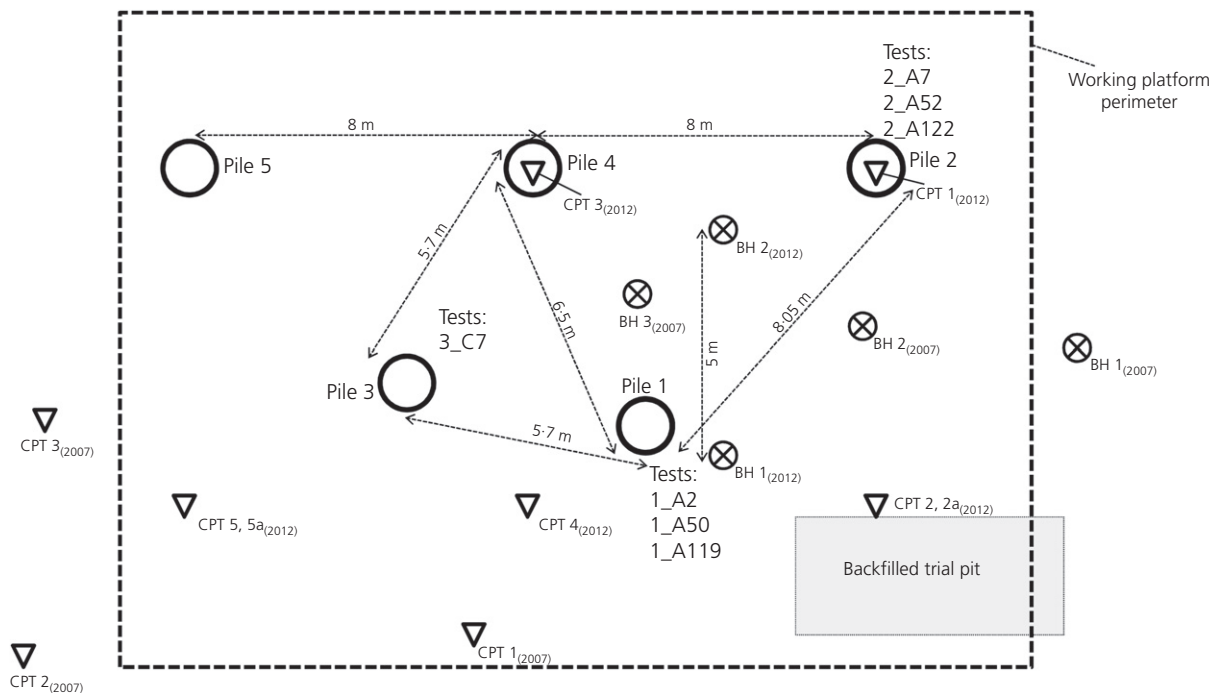
The results for pile 2 (Fig. 6(b)) are similar to those for pile 1 for the first two tests (2\_A7 and 2\_A52), but there was no further increase in capacity for the final test after 4 months (2\_A122). This last test shows an almost coincident load–displacement curve to the test performed after about 7 weeks (2\_A52). This may suggest that an application of lateral loading up to 10% of ultimate capacity had negligible influence on axial capacity, while the application of 50% ultimate lateral load had an adverse effect, possibly because a significant gap had developed between the pile and the chalk. In fact, the pile head lateral displacement measured at 50% of ultimate lateral load was about 18 mm. A similar dimension of the gap between the pile and chalk was measured.

By imposing force equilibrium on the piles and accounting that, in all tests with the exception of test 1\_A2, the chalk inside the pile was jointly lifted with the piles during loading; the average external unit shaft resistance ( $f_s$ ) has been





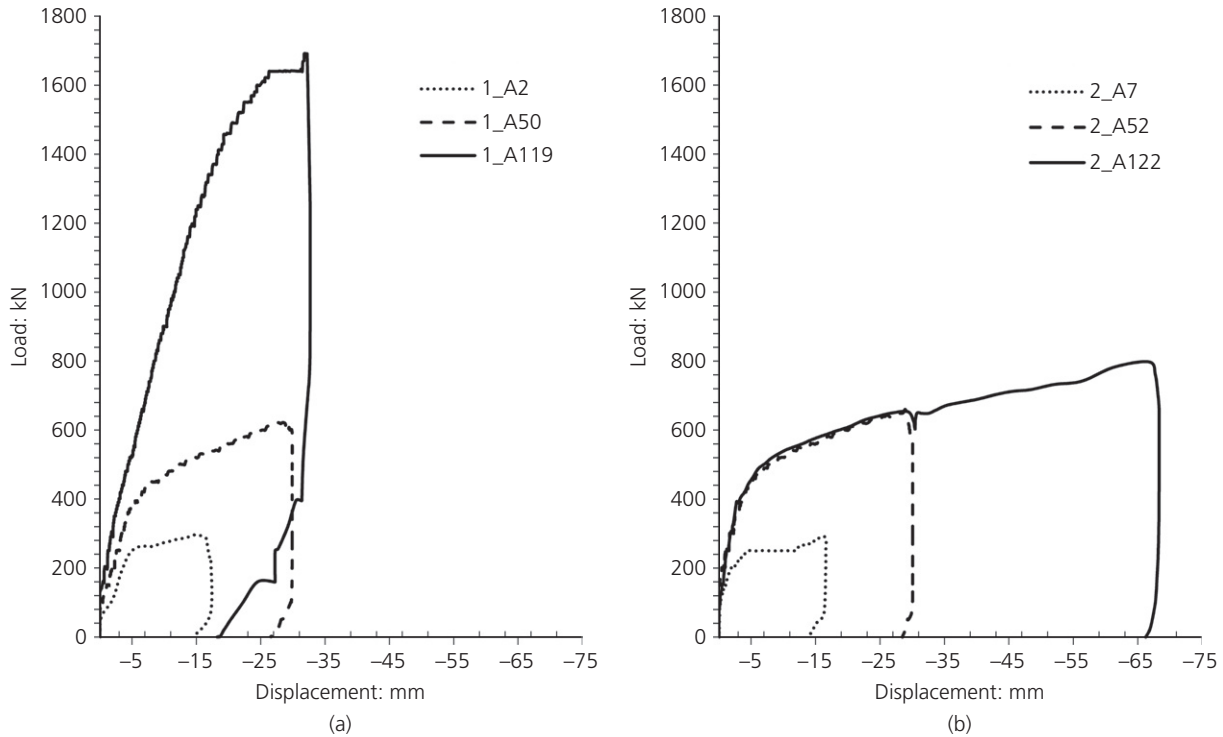
**Fig. 4.** Effect of pile driving: (a) top view of the pile and the chalk raised inside during driving, (b) side view of the pile showing remoulded annulus and (c) heaving of ground around the pile



**Fig. 5.** Test pile layout showing pile loading direction, borehole and CPT locations

**Table 2.** Summary of pile tests and results

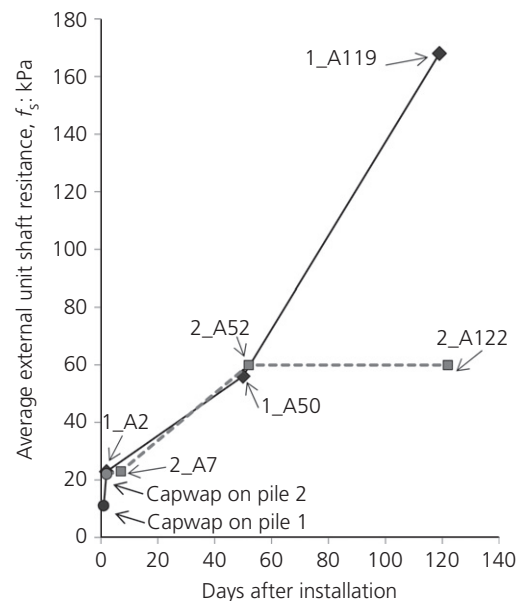
Pile number	Test name	Time after driving: days	Max load: kN	Average unit shaft resistance: kPa	Notes
1	1_A6	6	296	23	—
	1_A50	50	620	56	—
	1_A119	119	1691	168	—
2	2_A7	7	290	22	Lateral load up to 10% lateral capacity before the uplift test
	2_A52	52	650	60	Lateral load up to 10% lateral capacity before the uplift test
	2_A122	122	797	75	Lateral load up to 50% lateral capacity before the uplift test

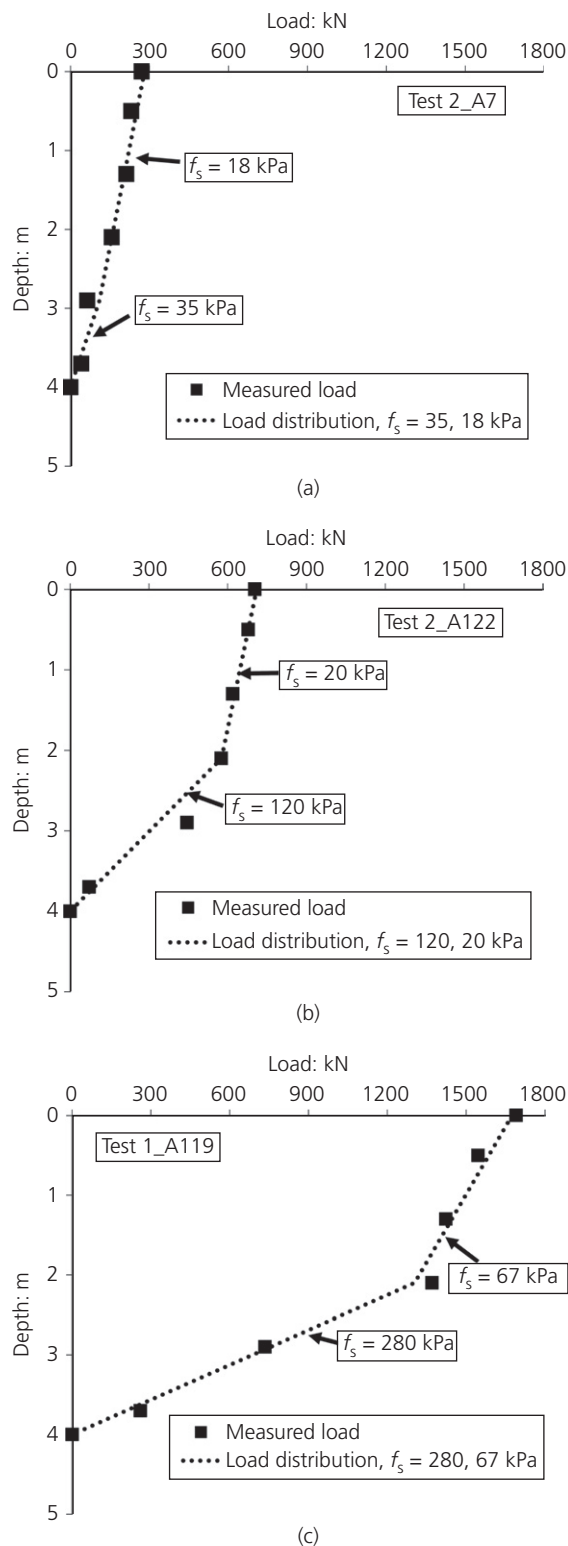
**Fig. 6.** Uplift load against pile head displacement response of (a) pile 1 and (b) pile 2

determined and plotted in Fig. 7. The results show that the 20 kPa unit shaft resistance recommended by Lord *et al.* (2002) was only measured a short time after pile driving (2–7 days). These results are consistent with the CAPWAP results, which are also reported in Fig. 7. A consistent increase in average external unit shaft resistance of up to about 60 kPa was measured for both piles after 7 weeks. A further increase of up to 168 kPa was measured for pile 1 after 4 months. However, the application of lateral load up to 50% the lateral capacity cancelled any further increase in unit shaft resistance for pile 2 beyond 7 weeks, since a value of about 60 kPa appears to have also been measured in test 2\_A122. The unit shaft resistance values in Fig. 7 are static long-term values and although they suggest that the Ciria C574 recommendation for the unit shaft friction of piles in low to medium density chalk may be conservative, the application of a two-way cyclic axial loading could result in a significant degradation in ultimate unit shaft resistance. Related to this are the observations of Diambra *et al.* (2014) that show a large cone sleeve friction degradation during cyclic CPT tests.

#### Distribution of shaft resistance

The strain gauge readings offer some insight into the distribution of shaft resistance along the pile. For these

**Fig. 7.** Average unit shaft resistance against time elapsed since pile installation



**Fig. 8.** Load distribution along the pile shaft at failure for: (a) test 2\_A7, (b) test 2\_A122 and (c) test 1\_A119

analyses, it has been assumed that negligible residual axial stresses would remain in the pile after driving based on the fact that the driving resistance of the chalk was low and axial stiffness of the pile was high. The measured load distribution has been determined simply by 'zeroing' the strain gauge readings before the start of each load test, as presented in Figs 8(a)–8(c) for three tests performed at different times after pile installation. The unit shaft resistance ( $f_s$ ) deduced

from the measured load distributions is also shown in the figures. The results indicate that a larger  $f_s$  is developed on the lower half of the pile as compared with the upper half.

## CONCLUSIONS

Two instrumented hollow steel piles with an external diameter of 0.762 m and 4 m EL were driven in grade A/B, low to medium density chalk and tested under uplift axial load at different times after installation. The following conclusions can be drawn from the analysis of the test results.

- During pile driving the chalk displaced up inside the pile, showing this was the preferential 'flow path'. Calculations showed that the amount of chalk rising inside the pile was equal to the volume occupied by the pile steel in the ground.
- A steady increase in uplift capacity was observed with elapsed time from pile installation. The measured capacity after 7 weeks was about twice the initial one (measured 2–6 days after driving), while the capacity after 4 months was six times the initial value.
- An average unit shaft resistance of 23 kPa was determined from the initial uplift tests performed a few days after driving. This is consistent with the Ciria C574 design recommendations for piles in low to medium density chalk. However, the results from uplift tests on the same piles showed that the ultimate average shaft resistance increased sevenfold (to 168 kPa) after 4 months. This increase is known as 'set-up' and may be attributed to excess pore pressure dissipation and possible rebonding of remoulded chalk particles.
- The ultimate shaft resistance can be affected by previous lateral loading. While the application of lateral loads up to 10% of the ultimate lateral resistance did not affect axial pile resistance, lateral loads reaching 50% of the ultimate lateral pile resistance resulted in a 65% reduction in ultimate shaft resistance relative to a pile that experienced no previous lateral loading.
- Strain gauge readings indicate the development of larger unit shaft resistance on the lower half of the pile as compared with the upper half.

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